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Effect of severe plastic deformation on internal friction of an Fe–26 at.% Al alloy and titanium

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Abstract

Low-temperature anelasticity related to dislocations and point defects in bcc Fe–26 at.% Al and in two hcp titanium alloys, severely deformed by high-pressure torsion, has been studied by mechanical spectroscopy. Up to five peaks have been observed; at least some of these can be classified as Hasiguti peaks. The stabilities of the internal friction peaks against heating are different. Mechanical spectroscopy is a useful tool to study the early annealing stages of severely plastically deformed alloys.
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1. Introduction

Nanostructured metals, generally defined as metals with grain sizes below 100 nm, possess very special chemical, physical and mechanical properties [1]. Among several different methods of production, severe plastic deformation, for instance, high-pressure torsion (HPT), is one of the most important and widely used routes; bulk materials with an extremely fine grain structure can be obtained in this way [2]. However, the deformation mechanisms in such ultrafine-grained metallic materials are not yet well understood; this refers particularly to anelastic and microplastic deformation. A useful technique for such a study is mechanical spectroscopy. In the past, several attempts were undertaken to study anelastic properties of HPT-deformed nanostructured metals, but most of them were confined to the grain boundary effect (in copper, aluminium, magnesium and nickel) which takes place at elevated temperatures. The subject of the present paper is the low-temperature anelasticity of an Fe–26 at.% Al alloy and titanium deformed by HTP.

The internal friction of Fe_3Al, which is a rather brittle intermetallic compound (deformation by bending ∼2% before fracture), has been reported for the undeformed state (prior to HTP) [3] and after conventional cold work [4], respectively. In the latter, a plateau-like peak was observed. It was supposed that this “D-peak” is due to dislocations and vacancies. However, the low ductility of Fe_3Al prevented a closer study of the influence of deformation. Two titanium alloys, Ti (grade 2) and Ti (VT1-0), have been chosen to represent hcp metals, and the mechanical properties and structure of the HPT-deformed VT1-0 were determined recently [5], whereas internal friction in cold worked titanium was reported much earlier [6]. Concerning the mechanisms of anelasticity (interaction of dislocations and different types of point defects), there should in principle be no difference between ordinary cold work and HPT. However, the sensitivity of the related internal friction peaks and their selectivity to heating should give a tool to study the early stages of recovery of severe plastically deformed metals.

2. Materials and methods

Disc-shaped samples of Fe_3Al and of titanium (about 10–12 mm in diameter and 1.0–1.5 mm in thickness) were subjected to HPT deformation at Institute of Physics of Advanced Materials, Ufa State Aviation Technical University, Ufa, Russia; see Table 1.

The shear strain γ in a certain point of the sample is a function of the distance R of this point from the centre: $\gamma = 2\pi NR/h$,

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Table 1
Materials and parameters of their deformation

Composition		Structure before deformation	Parameters of HPT deformation		
Alloy	Actual composition (mass%)		Number of turns, N	Pressure, P (GPa)	Shear strain, γ
Fe–26Al	14.4 Al (25.9 at.%Al)	bcc	1	3	160
Ti (grade 2)	0.1C—0.05N—0.25O—0.3Fe	hcp	5	6	780
Ti (VT1-0)	Ti—0.3Al—0.07C—0.04N—0.2O—0.25Fe—0.1Si	hcp	5	6	780

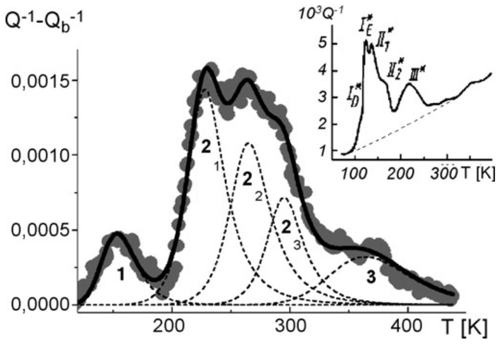

Fig. 1. Internal friction of an HPT-deformed Fe_3Al measured at $f \sim 2.2$ kHz, and computed five component peaks (see text). Inset: the internal friction spectrum of deformed and irradiated pure iron ($f \sim 0.5$ Hz) [8].

where N (here between 1 and 5) is the number of turns under a pressure from 3 to 6 GPa, and h is the thickness; in Table 1, γ is estimated for $R = 5$ mm and $h = 0.2$ mm. As shown in Table 1, HPT allows high degrees of deformation even for the brittle Fe_3Al.

Several heating runs were made for each specimen to measure temperature-dependent internal friction (TDIF) with successively increasing the uppermost temperature. Internal friction was determined by counting the number of freely decaying vibrations between two pre-selected amplitude levels. The dimensions of the specimens were about (10–12) mm × 1.5 mm × 0.2 mm, which had been cut out of the HPT-processed washer [7]. A standard vibrating-reed technique with electrostatic excitation and a high-frequency detection circuit was used to measure the internal friction Q^{-1} and the resonance frequency f of flexural vibrations during heating with 1 or 2 K/min, at temperatures between 90 and 900 K, in a vacuum of about 10^{-3} Pa. The specimen was placed in a cantilever-beam configuration by clamping at one end.

The microstructure of the HPT-processed specimens was examined by a scanning electron microscope DSM950 operating at 20 kV, and a transmission electron microscope Philips CM12 at an accelerating voltage of 120 kV.

3. Results and discussion

3.1. Fe–26 at.% Al

Fig. 1 shows the low-temperature range of TDIF curves in the HPT-deformed Fe–26 at.% Al alloy. The plateau-like D-peak in cold-worked Fe_3Al [4] is now shaped by HPT into five distinct components, which have been separated by a numerical decomposition procedure (dashed lines). To facilitate designation, we label the peak at about 150 K as 1, the group of internal friction peaks between 200 and 300 K as 2_1, 2_2 and 2_3, and the peak at about 370 K as 3, respectively. (Here, all temperatures are given for the actual resonance frequencies used.) A distinct group is formed by the peaks 2_n, which are reduced by annealing more effectively than the others, as shown in Fig. 2: these peaks are apparently caused by relatively unstable configurations or associations of point defects. They are accompanied by a typical step-like change in the resonance frequency corresponding to the "modulus defect" (with the modulus of elasticity E is proportional to f^2), which is most pronounced at the temperature of 2_1, according to the Kronig–Kramers relations. This modulus defect, as well as the peaks 2_n, is reduced step by step after the successive heating runs. After heating to 500 K at a rate of 1 K/min, neither a modulus defect nor the group of the peaks 2_n are detected.

Typically, the average grain size ($\bar{d}$) in as cast Fe_3Al is ~0.1 mm. Well-annealed (72 h at 573 K) Fe_3Al is characterised by $D0_3$ atomic order with clearly visible domains and antiphase boundaries, as shown in Fig. 3(a). After the HPT deformation

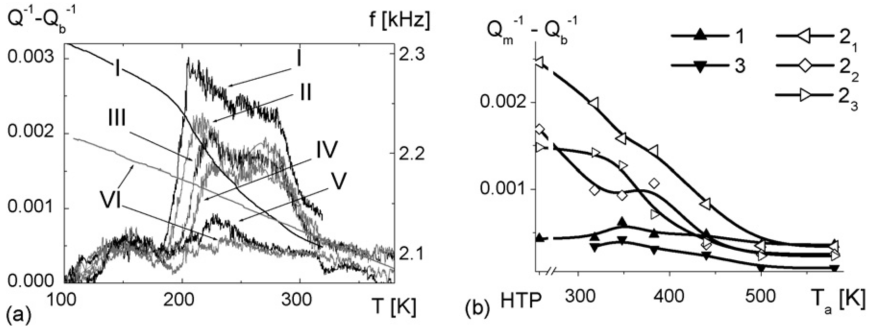

Fig. 2. (a) Internal friction and resonance frequency for subsequent temperature runs: I, as received (HPT-deformed); II, after heating to 320 K; III, to 350 K; IV, to 385 K; V, to 440 K; VI, to 500 K. (b) Influence of heating to different temperatures (T_a) on the separate peak heights. The peaks are specified in the right upper corner.

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